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LATERAL LASING AND ASE REDUCTION IN VECSELs (POSTPRINT)

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14. ABSTRACT
Vertical external cavity surface emitting lasers (VECSELs) are attractive for many applications due to their high-power, high-brightness outputs. In order to power scale the devices, the pump spot size should be increased. However, the large pump area greatly amplifies the guided spontaneous emission in the epitaxial plane. In order to efficiently power scale the devices, amplified spontaneous emission (ASE) and lateral lasing must be reduced. We begin by first reporting on the temperature dependence of the phenomena. Particularly, since the quantum well gain and bandgap are functions of temperature, ASE and lateral lasing are greatly dependent on the operating temperature as well as the pump power. The easiest method of quantifying the affect of ASE and lateral lasing is by removing the Fabry-Perot cavity formed by the chip edges. We have chosen two different methods: Reducing the Fresnel reflections by patterning the edges of the sample, and depositing a layer of Ge on the edges of the VECSEL chip as the high index of refraction for Ge should reduce the Fresnel reflections and the absorption properties in the NIR regime should also act to prevent feedback into the pump area. Our research shows both of these methods have increased the performance and visibly decreased the amount of lateral lasing seen in the devices.

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Lateral Lasing and ASE Reduction in VECSELs

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Abstract

Vertical external cavity surface emitting lasers (VECSELs) are attractive for many applications due to their high-power, high-brightness outputs. In order to power scale the devices, the pump spot size should be increased. However, the large pump area greatly amplifies the guided spontaneous emission in the epitaxial plane. In order to efficiently power scale the devices, amplified spontaneous emission (ASE) and lateral lasing must be reduced. We begin by first reporting on the temperature dependence of the phenomena. Particularly, since the quantum well gain and bandgap are functions of temperature, ASE and lateral lasing are greatly dependent on the operating temperature as well as the pump power. The easiest method of quantifying the affect of ASE and lateral lasing is by removing the Fabry-Perot cavity formed by the chip edges. We have chosen two different methods: Reducing the Fresnel reflections by patterning the edges of the sample, and depositing a layer of Ge on the edges of the VECSEL chip as the high index of refraction for Ge should reduce the Fresnel reflections and the absorption properties in the NIR regime should also act to prevent feedback into the pump area. Our research shows both of these methods have increased the performance and visibly decreased the amount of lateral lasing seen in the devices.

Keywords: VECSEL, ASE, Lateral Lasing

1. Introduction:

Optically pumped vertical external cavity surface emitting lasers (VECSELs) have proven to be capable of achieving multiwatt high-brightness emission.[1,2] However, ASE and lateral lasing limit the maximum pump spot diameter and thus, power scaling of the device.[3] Inside the pumped region of a VECSEL, spontaneous emission is naturally emitted at all possible angles. Due to the index guiding from the device layer structure, photons emitted in the epitaxial plane are trapped by these guiding layers and amplified over the pump region. This amplified spontaneous emission (ASE) can lead to lasing in the lateral plane if the edges of the chip supply sufficient feedback.

To realize power scaling of the VECSEL, the pump spot size should be increased and the operating temperature should be decreased.[4] However, the large pump area greatly increases the gain length in the lateral plane significantly amplifying the guided spontaneous emission. In addition, the semiconductor gain is intrinsically temperature dependent since the bandgap of semiconductor and the quasi-Fermi-Dirac distribution of the carriers are a function of temperature. As the temperature of the device is decreased the gain increases. This increase in gain also results in an increase in ASE and lateral lasing as we will see later.

There is one other aspect that greatly promotes lateral lasing. As the device is pumped, the active region begins to heat. The energy bandgap of semiconductors tends to decrease as the temperature is increased since the increasing temperature causes an increase in interatomic spacing thus reducing the potential seen by the carriers in the material and reducing the energy bandgap.[5] For the longitudinal mode of a VECSEL, this heating causes the optical resonance of the microcavity and the quantum well gain peak to tune to longer wavelengths at the rate of ~ 0.1 nmK^{-1} and ~0.3 nmK^{-1}, respectively.[6] Since optical pumping is used, the temperature in the material outside of the pumped area is then colder due to the fact that the thermal flows in the device are primarily perpendicular to the surface. Because of this the band gap in the pumped region is less than that in the surrounding area. This results in the areas surrounding the pump spot to

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be transparent to the spontaneous emission. The edges of the VECSEL chip then can act as mirrors and provide feedback for the ASE and lateral lasing can occur.

2. VECSEL Structure and Device Fabrication

Two different structures were used in the experiments. For the first, a highly strained compensated InGaAs/AlGaAs/GaAsP multi-quantum well in a resonant periodic gain structure was designed using rigorous many-body microscopic quantum design tools and 3D optical/thermal modeling of the device to operate near 1178nm.[7] The VECSEL structure consists of 10 repeats of compressive strained InGaAs quantum wells. Each quantum well is 7-nm thick and surrounded by GaAsP strain compensation layers and AlGaAs barriers, in which the 808- nm pump emission is absorbed. The thickness and compositions of the layers are optimized such that each quantum well is positioned at the antinodes of the cavity standing wave to provide resonant periodic gain (RPG) in the active region.[8,9] A high reflectivity (R > 99.5%) DBR stack made of 21-pairs of AlGaAs/AlAs is grown on the top of the active region. To avoid premature thermal rollover, a detuning between quantum well gain peak and microcavity resonance of about 30 nm is introduced which compensates the thermal detuning at higher temperatures and powers at the expense of a slight increase in threshold power. The second was a 980nm VECSEL consisting of 15 repeat single 8nm quantum well structure using the same design techniques as the first sample.

Both structures used the same method for efficient heat dissipation. A thin Ti/Au metallization layer is deposited on the epitaxial side of the wafer and CVD diamond heat spreader. The sample is then solder bonded to the CVD diamond heat spreader using indium solder. The GaAs substrate is then completely removed by selective wet chemical etching. The remaining semiconductor, consisting of a DBR-stack and RPG active layers, is about 6 um thick allowing efficient heat extraction at high pumping energy.

3. Temperature Dependence:

The 1178nm VECSEL structure was chosen for looking at the temperature dependence of lateral lasing since the large quantum defect heat from the active region should generate more waste heat in the pumped region thus enhancing the lateral lasing effect. An 1178nm sample VECSEL was tested in linear cavity of length ~ 22cm with an output coupler that was 4% transmissive. The pump spot was approximately 480um in diameter which resulted in single transverse mode operation. Figure 1 shows the output from the device at three different temperatures. Typically it is expected that decreasing the temperature of the heat sink will increase the threshold and increase slope efficiency leading to higher output powers. In this case, we notice that the output increases from 25C to 15C, but at 5C the output becomes unstable and actually decreases.

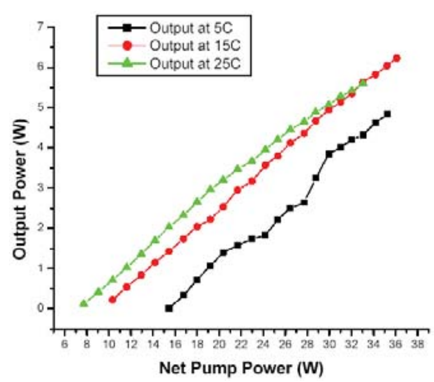


Figure 1. Output powers from linear cavity at three different temperatures. As the temperature decreases, lateral lasing becomes more prevalent adding instabilities to the longitudinal VECSEL mode.

The output is decreases and becomes unstable due to the gain competition between the longitudinal lasing mode of the VECSEL and that of the lateral lasing.[10] Figure 2 shows a series of pictures taken during the test. The pictures show the lateral lasing scattered from the edge of the chip at various temperatures and levels of net pump power. As can be seen, there is virtually no lateral lasing when the temperature of the heat sink is held at 25C. This results in the steady output shown in figure 1. Again, at 15C, we see that there is some lateral lasing now evident, but this appears to have little affect on the stability of the output and we see an increase in performance as is expected. As we cool the sample to 5C we now notice that the lateral lasing becomes very intense. As we cooled the device the gain in the active region increased. This caused a FP resonator to be formed in the lateral plane that competed with the axial lasing mode. This is the reason the output became unstable.

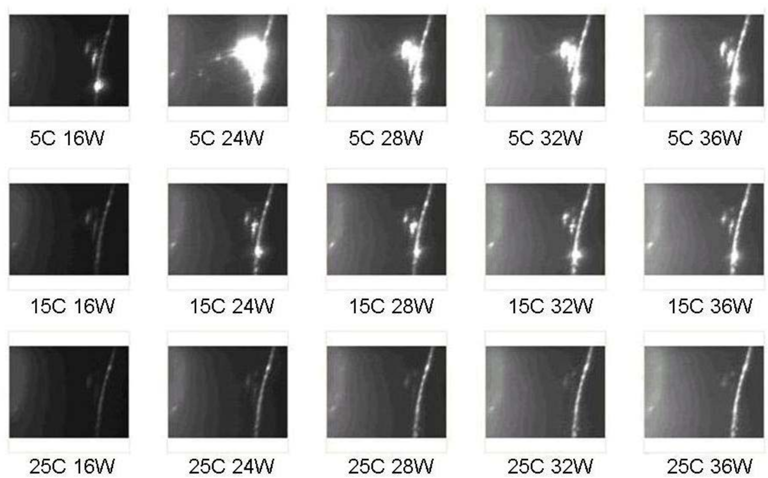


Figure 2. The top row shows the lateral lasing scattered the the chip edge when the heat sink is held at a temperature of 5C. The middle and last rows show heat sink temperatures of 15C and 25C respectively. The images show that as the device temperature is decreased, Lateral lasing becomes more prevalent.

4. Edge Mirror Elimination

Figure 3 is an image of a 4mm in diameter sample processed in a similar manner (i.e. Ti/Au metal evaporated,solder mounting using evaporated indium, substrate removal, and AR coating). However, Instead of being square in shape as the previous sample, the edge of the sample is "starred" wherein any ASE which impinges on the surface is not Fresnel reflected back into the cavity, but is glancing-angle reflected much like a light trap into the points of the star. This image is taken using a silicon CCD while pumping at 808nm and filtered such that we are primarily observing the photoluminescence. As is evident in figure 3, the points of the star are indeed brightest, showing that in-plane guided ASE is indeed making it to the points, but there is no lateral lasing observed in this sample.

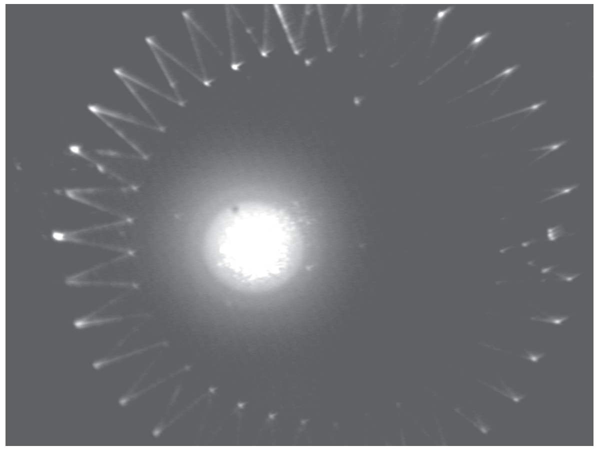


Figure 3. Surface PL image taken from a sample that was etched in a star patterm quench direct feedback from the edge.

Figure 4 is a comparison of the “star mesa” seen in figure 3 and a “circular mesa” sample taken 5mm away from the star sample on the same wafer. Each sample is approximately 4mm in diameter, and we can presume the epitaxial growth varies relatively slowly on this scale, so take the two chips to be epitaxially identical. An area was pumped near the center where the laser performed the best and removed the external mirror to avoid clamping the carriers at threshold, and pumped for several different powers. We see the DBR and sub-cavity resonances (DBR edge at about 940nm, subcavity at about 983nm). For the smaller pump area (500µm diameter), we see lateral lasing showing up between 4.3 and 5.5 kW/cm^2 in the circular mesa, although we reached 8kW/cm^2 (pump source limited) in the star mesa with no lateral lasing evident. For further comparison, another laser from this wafer about 1mm away was processed. The lasing threshold (500um diameter) was about 3 kW/cm^2.

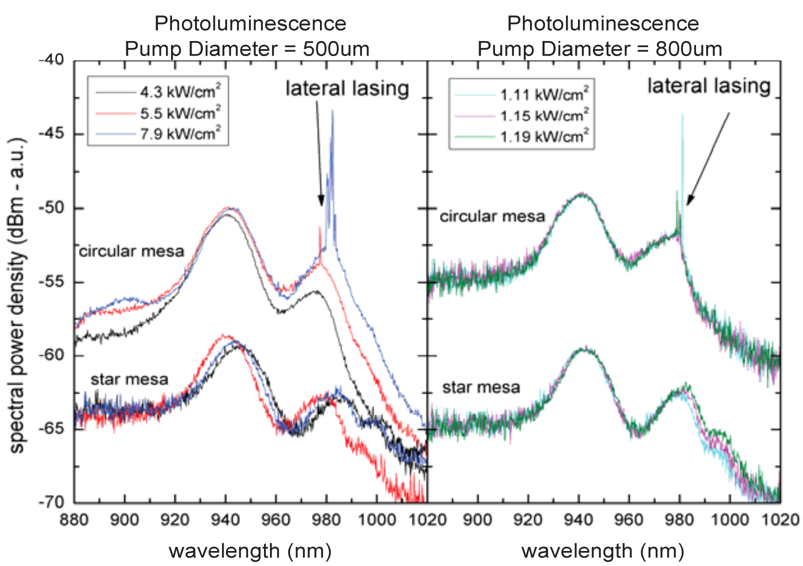


Figure 4. Surface-emitting photoluminescence for different pump spot sizes for two different chip geometries. There is an artificial offset to separate the spectra.

5. Germanium Deposition

There is no perfect way to quantify how much power is lost due to ASE and lateral lasing since there is now way to directly turn it on and off.[3] However, if we first induce lateral lasing and then suppress it, we should be able to gain a better understanding of the detrimental effect it has on the VECSEL output. In order to quantify how much power is lost, we must first be able to eliminate the lateral lasing. One way to eliminate the lateral lasing is to damage the edges of the sample, or etch the sample into an unusual shape thus eliminating the lateral cavity as we have seen in the previous section. This may eliminate the lateral cavity, but it does not prevent reflections from the edge of the sample passing through the pumped region for further amplification. Because of this we choose to deposit a thin germanium (Ge) film on the edges of the sample. Because of the large refractive index n = 4.38, k = 0.12 at 1178nm[11], this should reduce the Fresnel reflection coefficient at the sample edges and absorb the radiation inside the Ge film preventing feedback into the pumped region.

Here we again used an 1178nm VECSEL structure to make use of the heating caused by the large quantum defect. In addition, the device was also carefully processed to ensure neatly cleaved edges to maximize the mirror reflectivity in the lateral plane. This resulted in a device that had very visible lateral lasing at 15C. The device was first mounted on a translation stage in a ~ 22cm linear cavity with a 98% 30cm ROC output coupler with a ~480um pump spot size on the chip. The performance of the chip was tested at 15C and the location of the pump spot was measured using the micrometer on the translation stage. The sample was then removed and a thin 100nm layer of Ge was evaporated on two edges of the sample as shown in figure 5. After the Ge was deposited, the sample was mounted on the same set up with the cavity set in the same configuration as before. The chip was then translated to the same location and the performance was again recorded. As seen in figure 6a, after the Ge was deposited, the lasing threshold remained constant, but the slope efficiency increased and the maximum output power of the device increased from 2.47W to 2.91W. The same test was performed using a 620um pump spot diameter as well. For this we used an 8cm linear cavity with 98% 75cm ROC output coupler. Again, figure 6b shows that the threshold was constant, but the slope efficiency increased and the maximum output power increased from 2.86W to 3.44W.

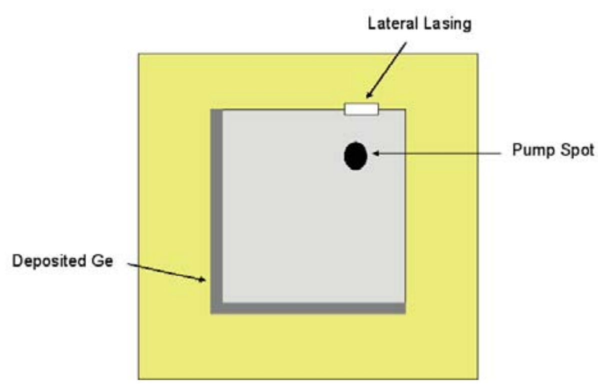
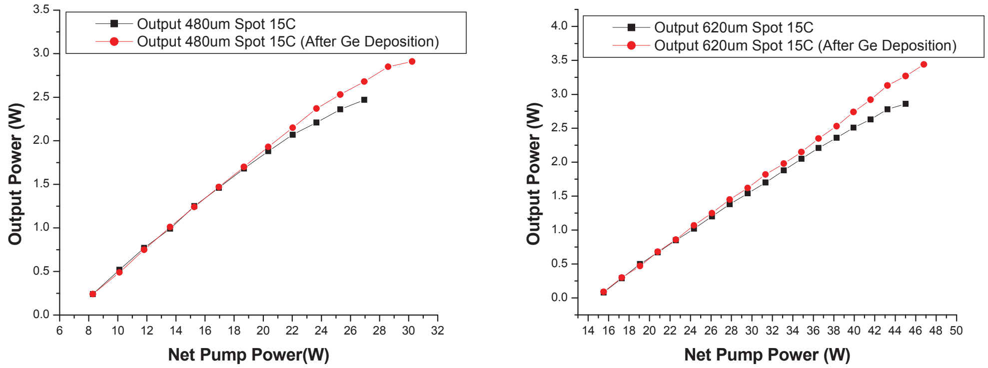


Figure 5. Location of the pumped area and deposited Ge. The lateral lasing was observed from the scatter at the edge of the chip.



a) b)

Figure 6. a) Output power from a 480um pump spot diameter before and after Ge deposition on two edges of the sample. b) For the same sample the pump spot diameter is increased to 620um and a similar increase in performance is observed before and after Ge deposition.

In the previous experiments, we saw that the introduction of absorbing regions onto two edges resulted in an increase of output power by approximately 20% for two different pump diameters. For the next experiment, we again prepared a chip to induce lateral lasing, and specifically cooled the heat sink to 0C and used a large pump spot of around 550um inside a linear cavity of 6.4cm with 98% 30cm ROC output coupler to again provide VECSEL lasing in a single transverse mode. Here we coated only the one edge of the sample that was in the path of the lateral lasing, but did not interfere with the scatter that we observed from the edge of the sample. Figure 5 shows the performance of the device before and after Ge deposition. Here, the threshold again remained about the same, but the slope efficiency is slightly reduced presumably caused by damage to the sample after extensive testing. However it is noticed that the output of the device still increased. Figure 7 shows the imaged pump spot at three different levels of pumping before and after Ge deposition. Prior to Ge deposition, the lateral lasing at the edge of the chip is clearly visible, but after Ge deposition, there is no visible sign of lateral lasing.

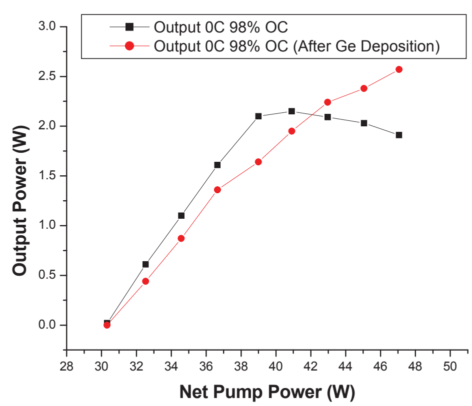


Figure 7. Output before and after Ge deposition on one side of an 1178nm sample.

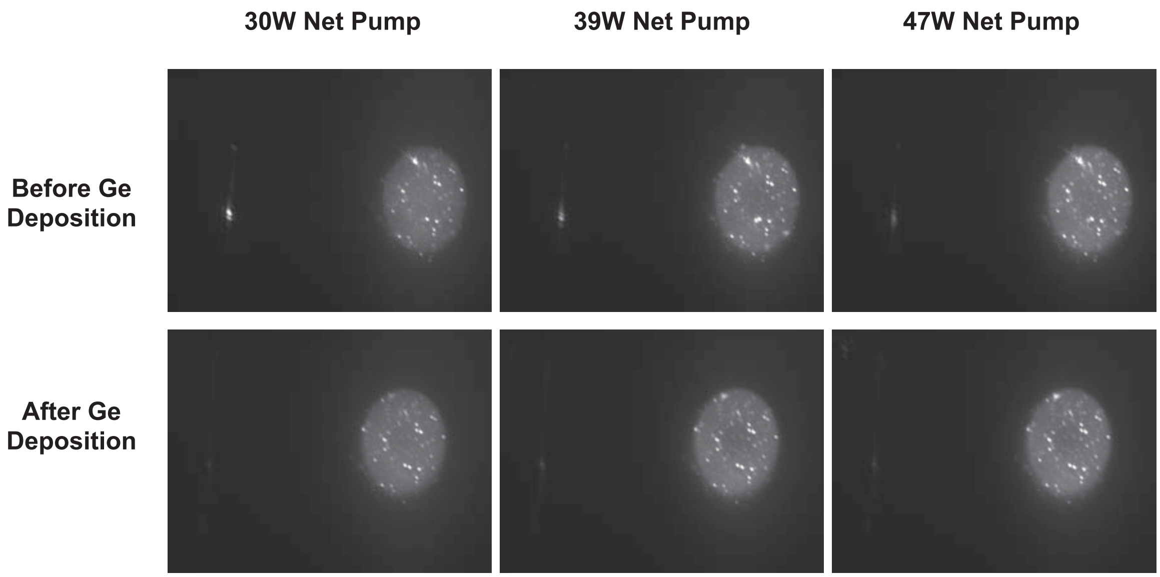


Figure 8. The top row shows the lateral lasing scattered from the left edge of the sample prior to coating one edge of the sample with Ge at three different net pumping levels. The bottom row shows the same spot on the sample after Ge deposition when no scatter from lateral lasing is observed.

6. Conclusion

The research to date clearly shows a strong temperature dependence of lateral lasing which inhibits power scaling of VECSEL's. Because lateral lasing occurs when large amounts of ASE are accompanied by feedback we saw that by either patterning the edges or introducing an absorbing region around the edges we could extinguish the lateral lasing indicating a directional loss in ASE by means of a reduction of gain. By combining our methods of edge mirror destruction and Ge deposition, it will be possible to eliminate lateral lasing and reduce directionally the ASE and thus increasing the performance of VECSELs. This should allow for not only the decrease in operating temperature of the device, but also allow for the use of larger pump areas which will in turn increase the beam quality and slope efficiencies resulting in higher output powers.

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